Improved Astrometry and Photometry for the Luyten Catalog. I. Bright Stars

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ABSTRACT

We outline the construction of an updated version of the *New Luyten Two-Tenths* (NLTT) catalog of high proper motion stars, which will contain improved astrometry and photometry for the vast majority of the $\sim 59,000$ stars in NLTT. The bright end is constructed by matching NLTT stars to Hipparcos, Tycho-2, and Starnet; the faint end by matching to USNO-A and 2MASS. In this first paper, we detail the bright-end matching procedure. We show that for the majority of stars in his catalog, Luyten measured positions accurate to $1''$ even though he recorded his results much more coarsely. However, there is a long tail of position errors, with one error as large as $11°$. Proper-motion errors for the stars with small position errors are $24\,\mathrm{mas\,yr^{-1}}$ ($1\,\sigma$) but deteriorate to $34\,\mathrm{mas\,yr^{-1}}$ for stars with inferior positions. NLTT is virtually 100% complete for $V \lesssim 11.5$ and $|b| > 15°$, but completeness in this magnitude range falls to $\sim 75\%$ at the Galactic plane. Incompleteness near the plane is not uniform, but is rather concentrated in the interval $-80° < \ell < 20°$, where the Milky Way is brightest.

Subject headings: astrometry – catalogs – methods: statistical

1. Introduction

More than two decades after its final compilation, the *New Luyten Two-Tenths Catalog* (NLTT) of high proper-motion stars ($\mu > 0''\!.18\,\mathrm{yr^{-1}}$) (Luyten 1979, 1980; Luyten & Hughes 1980) and its better known subset, the *Luyten Half-Second Catalog* (Luyten 1979, LHS) ($\mu > 0''\!.5\,\mathrm{yr^{-1}}$), continue to be a vital source of astrometric data. They are still mined for nearby stars (Reid & Cruz 2002; Jahreiss, Scholz, Meusinger, & Lehmann 2001; Scholz,

Meusinger, & Jahreiss 2001; Gizis & Reid 1997; Henry, Ianna, Kirkpatrick, & Jahreiss 1997), subdwarfs (Gizis & Reid 1997; Ryan 1992, 1989), and white dwarfs (Reid, Liebert, & Schmidt 2001; Schmidt et al. 1999; Liebert, Dahn, Gresham, & Strittmatter 1979; Jones 1972; Luyten 1970, 1977). NLTT is at the center of the controversy over whether halo white dwarfs can contribute significantly to the dark matter (Reid, Sahu, & Hawley 2001; Oppenheimer et al. 2001; Flynn et al. 2001); and it is the primary source of candidates for astrometric microlensing events to be observed by the *Space Interferometry Mission (SIM)* (Salim & Gould 2000). Despite the advent of many new proper-motion surveys, including Hipparcos (ESA 1997), Tycho-2 (Høg et al. 2000), Starnet (Röser 1996), UCAC1 (Zacharias et al. 2000), as well as deeper but more localized surveys: SuperCOSMOS Sky Survey in the south (Hambly et al. 2001; Hambly, Davenhall, Irwin, & MacGillivray 2001), Digital Sky Survey (DSS)-based survey in the Galactic plane (Lepine, Shara, & Rich 2002), search for $\mu > 0\rlap{.}''4\,\mathrm{yr}^{-1}$ stars in $\sim 1400\,\mathrm{deg}^2$ (Monet et al. 2000), EROS 2 proper motion search in $\sim 400\,\mathrm{deg}^2$ of high latitude fields (EROS Collaboration et al. 1999), and MACHO search in $50\,\mathrm{deg}^2$ towards the bulge and the LMC (Alcock et al. 2001), NLTT remains unchallenged as a deep, all-sky, proper motion catalog.

NLTT is an all-sky position and proper-motion (PPM) catalog with a proper-motion threshold of $\mu_{\mathrm{lim}} = 180\,\mathrm{mas\,yr}^{-1}$. It extends to $V \sim 19$ over much of the sky, although it is less deep ($V \lesssim 15$) within about $10°$ of the Galactic plane and also in the celestial south ($\delta < -30°$). In addition to PPM, NLTT lists somewhat crude photographic photometry in two bands (B_{NLTT}, R_{NLTT}), rough spectral categories, as well as important notes on some individual stars, primarily common proper motion (CPM) binaries.

To be sure, the newer catalogs have superseded NLTT in certain domains. By observing a large fraction of the brighter ($V \lesssim 11$) NLTT stars, Hipparcos obtained vastly superior astrometry and photometry for about 13% of NLTT, although in its magnitude limited survey ($V < 7.3$–9.0) it did not find any significant number of new high proper-motion stars not already catalogued by Luyten. Tycho-2, which combined re-reduced Tycho observations of 2.5 million stars with 144 ground-based catalogs (most notably the early 20-century Astrographic Catalog) to derive proper motions, includes PPM and photometry for several thousand additional NLTT stars, and also contains several hundred previously unknown bright ($V \lesssim 11$) high proper-motion stars. However, neither Hipparcos nor Tycho-2 probes anywhere near the faint ($V \sim 19$) limit of NLTT. Moreover, their overlap with NLTT has never been systematically studied. UCAC (US Naval Observatory CCD Astrograph Catalog) is in the process of delivering a new all-sky PPM catalog down to $R \sim 16$ based on CCD observations. The first release (UCAC1) covers 80% of the Southern hemisphere. While its photometry is only for a single band (close to R), UCAC1 can easily be matched to 2MASS (Skrutskie et al. 1997) with its JHK photometry, effectively creating a multi-

wavelength PPM catalog. Unfortunately, the current release, UCAC1, excludes most of the NLTT high proper-motion stars, due to absence of these stars in Southern parts of USNO-A2 catalog (Monet 1998), which was used as a first epoch. (USNO-A2, and its earlier version USNO-A1, Monet 1996, were derived by measuring first generation Schmidt plates.) High proper-motion stars pose an especially difficult problem for automated catalog construction: counterparts of slow-moving stars can be reliably identified at different epochs, but fast-moving ones are easily confused with pairs of unmatched, but unrelated stars, or even with spurious objects. These problems grow rapidly worse near the magnitude limit and towards the Galactic plane. Without either new and robust (but difficult to write) algorithms or a vast investment of manual labor, the only routes open in the face of these difficulties are to eliminate the potential high proper-motion stars from the new catalogs or to include them but to acknowledge that many may be spurious. These two approaches have been respectively adopted by UCAC1 and Starnet. (Starnet derives its proper motions for 4.3 million stars by combining the Nesterov, Kislyuk, & Potter 1990 reduction of Astrographic Catalog with GSC 1.0, Lasker et al. 1990.)

There are two other PPM catalogs whose release is promised in the near future, USNO-B (Monet 2000) and GSC-II (Lasker et al. 1998, also known as GSC 2.3). Both are based on photographic astrometry and photometry down to or beyond the NLTT limit of $V \sim 19$. They use a combination of first and second generation Schmidt plates to determine proper motions. Neither project has stated explicitly how they will handle high proper-motion stars.

Ultimately, space missions such as *FAME*, *DIVA*, and/or *GAIA* will produce reliable catalogs of high proper-motion stars, since each star is observed hundreds of times with great astrometric precision, thus eliminating the possibility of false matching. However, NLTT stars that are fainter than the *FAME* or *DIVA* survey limit of $R \sim 15$ cannot be observed by them unless they are securely located prior to the mission (Salim, Gould, & Olling 2002). Hence, this is yet another reason for obtaining improved astrometry for these stars.

While NLTT has proven incredibly valuable, it also has significant shortcomings. As mentioned above, its two-band photometry is relatively crude, so that classification of stars using the NLTT reduced proper motion (RPM) diagram (one of the main motivations for constructing the catalog) is rather uncertain: white dwarfs are easily confused for subdwarfs, as are subdwarfs for main-sequence stars. Very few of the NLTT stars have their optical magnitudes in standard bands available in the literature. This problem is not easily resolved by matching with other catalogs that have better photometry, such as USNO-A (photographic B_{USNO} and R_{USNO}: $\sigma \sim 0.3$) or 2MASS (JHK: $\sigma \sim 0.03$). This is because although a large fraction of NLTT stars have fairly precise ($\sim 10''$) positions, a significant

minority have much larger errors, making automated identification of counterparts in other catalogs quite difficult.

Some applications require much higher precision proper motions than NLTT's characteristic 20–30 mas yr^{-1}. For example, we (Salim & Gould 2000) have previously found that even when faint NLTT stars can be identified in USNO-A (thus establishing their POSS I 1950s positions to ~ 250 mas) the NLTT proper-motion errors propagate to create $\sim 1\farcs5$ position errors in 2010, too large to reliably predict viable astrometric microlensing events to be observed by *SIM*, and so measure precisely the mass of the lens (high proper motion star). Recently we have found that these errors can be reduced to ~ 100 mas, which is quite adequate for our purposes, by matching NLTT stars first to USNO-A and then to 2MASS. We therefore began to create our own private catalog of NLTT/USNO-A/2MASS matches. While this catalog is highly useful for our specific project, it has many spurious identifications and is too incomplete to be suitable for general release.

However, as we have worked with our provisional NLTT/USNO-A/2MASS catalog, we have gradually become aware of the wide range of potential applications to which this catalog could be put. For example, the resulting $V - J$ RPM diagram (where V is calibrated from $B_{\rm USNO}$ and $R_{\rm USNO}$) permits a much more reliable separation of different classes of stars than did the original $B_{\rm NLTT} - R_{\rm NLTT}$ RPM diagram. Study of this diagram will be useful in its own right, but can also guide the interpretation of RPM diagrams constructed of NLTT stars present in SDSS (York et al. 2000), making use of excellent SDSS photometry and SDSS/USNO-A derived proper motions. An updated NLTT catalog could also be exploited to study binarity as a function of stellar population and to find new wide-binary companions of NLTT stars. Finally, it would permit a more thorough study of some of NLTT's own properties, including most especially its completeness. NLTT's completeness (or lack thereof) is central to the debate over the possibility that a significant fraction of the dark matter can be in halo white dwarfs. Flynn et al. (2001) argued that if NLTT were assumed to be complete at the bright end ($V \lesssim 13$), then one could use a bootstrap-type procedure to show that it is also close to complete at the faint end. There are two problems with this argument. First, it has never been demonstrated that NLTT is in fact complete at the bright end. Second, Monet et al. (2000) argued that the bootstrapping procedure was not valid, at least in its original form.

Here, we present the first step in the construction of an updated NLTT catalog: matching bright NLTT entries with those in more recent and higher-precision catalogs, primarily Hipparcos and Tycho-2, but also Starnet. By doing so, we characterize both NLTT's PPM errors and its completeness at the bright end for the first time. These results are of interest in their own right, but they also serve to guide our search procedure for USNO-A/2MASS

counterparts at fainter magnitudes.

That faint-end search will be the subject of Paper II of this series. The general approach will be to match (circa 1950) USNO-A stars with their (circa 2000) 2MASS counterparts using NLTT (1950 epoch) positions as a rough guide as to where to find USNO-A counterparts, and NLTT proper motions to predict the positions of their 2MASS counterparts. To correctly apply this approach and to understand its limitations, one must have a good grasp of the NLTT PPM error distributions, and for this it is best to compare NLTT with other PPM catalogs.

The bright-end and faint-end searches are complementary. On the one hand, Hipparcos/Tycho-2/Starnet become highly incomplete for $V \gtrsim 12$, and so cannot probe faint magnitudes. On the other hand, the POSS plates that were scanned to produce USNO-A saturate for $V \lesssim 11$, leading to increasingly unreliable photometry, astrometry, and even identifications at bright magnitudes. Nevertheless, these searches do have some overlap at intermediate magnitudes, and we will exploit this overlap to check each method against the other. Hence, we push the bright-end search as faint as we can, incorporating Starnet (with its spurious high-proper motion stars). And we push the faint-end search as bright as we can, eliminating only the Hipparcos/NLTT matches before beginning the search.

Bakos, Sahu, & Nemeth (2002) have recently located 96% of stars from the LHS catalog (which contains about 8% of all NLTT entries). They manually identified and measured the positions of LHS stars in DSS1 and DSS2 images. The revised coordinates have an accuracy of $\sim 2''$. Moreover, now that most LHS stars (even those with really bad NLTT positions) have been located, their positions can be easily further refined by matching them to other astrometric catalogs, which the authors did for some bright stars using the Tycho-2 and Hipparcos catalogs.

In § 2, we analyze the NLTT PPM errors, and in § 3 we describe the construction of the revised catalog. In § 4 we discuss NLTT's completeness. In § 5, we study the RMS differences between proper motions from NLTT and those of the three modern catalogs. In § 6, we estimate the rate of false matches of our procedure. Finally, in § 7, we perform an additional check on the efficiency and reliability of our matches by cross-checking with the Bakos, Sahu, & Nemeth (2002) catalog. In Paper II we will merge the results of the bright-end and faint-end searches and make the resulting catalog publicly available. This first release of our catalog will likely take place prior to the full release of 2MASS data, and hence will include only the 47% of the sky covered by the 2MASS release. The catalog will be updated following the full 2MASS release.

2. NLTT Astrometric Errors

To match NLTT stars with counterparts found in other catalogs, we have to start with NLTT's positions and proper motions. To devise a search strategy, it is therefore crucial that we first evaluate the error distributions of these quantities. Positions in NLTT are nominally given to two different levels of precision, indicated by a flag: in right ascension (RA), either 1 second or 6 seconds of time and in declination (DEC), either $0\rlap{.}'1$ or $1'$ of arc. The inferior precisions are the rule in the south ($\delta < -45°$), and the superior precisions are the rule in the north, although for $\delta > 80°$, the RA is given at nominally inferior precision because 6 seconds of time still corresponds to a relatively small arc.

What is the actual PPM error distribution for the $\sim 54,000$ NLTT entries with nominally good positional precision? To investigate this, we first select only Tycho-2 stars with proper motions $\mu > 180\,\mathrm{mas\,yr^{-1}}$, i.e., the same limit as of NLTT. Using Tycho-2 proper motions (having typical errors of just $2\,\mathrm{mas\,yr^{-1}}$), we propagate their positions back to 1950, the epoch of NLTT. We then find all NLTT entries whose catalog coordinates lie within $3'$ of each Tycho-2 star – many times larger than the nominal positional accuracy. To ensure a high level of confidence that the counterpart is real, we restrict consideration to stars for which there is one and only one Tycho-2/NLTT match, and for which the unique NLTT match does not have a flag indicating an inferior-precision measurement. Finally, we eliminate 84 matches for which the Tycho-2 proper motion disagrees with the NLTT proper motion by more than $75\,\mathrm{mas\,yr^{-1}}$. Figures 1 and 2 show the position differences (NLTT − Tycho-2) of the resulting 6660 unique matches, on small and large scales respectively. The central portion of this distribution (Fig. 1) exhibits an obvious rectangle with dimensions ($1\,\mathrm{s} \times 6''$), i.e., exactly the precisions imposed by the rounding truncation of the catalog entries. Hence, one can deduce that for the majority of the entries within this rectangle, Luyten actually measured the positions to much better precision than they were recorded into NLTT. Also obvious in this figure is a halo of stars that have characteristic errors that are of order the discretization noise. We therefore model the distribution of Luyten's position measurements as being composed of two populations, with intrinsic Gaussian measurement errors (in arcsec) of σ_1 and σ_2. Given the discretization of the reported positions, the distribution of residuals in DEC ($\Delta\delta$) should therefore be,

$$
\begin{aligned}
P(\Delta\delta) \;=\; \frac{1}{2w}\Big\{ & q\Big[\mathrm{erf}\Big(\frac{c + w/2 - \Delta\delta}{\sigma_1}\Big) - \mathrm{erf}\Big(\frac{c - w/2 - \Delta\delta}{\sigma_1}\Big)\Big] \\
& + (1-q)\Big[\mathrm{erf}\Big(\frac{c + w/2 - \Delta\delta}{\sigma_2}\Big) - \mathrm{erf}\Big(\frac{c - w/2 - \Delta\delta}{\sigma_2}\Big)\Big]\Big\},
\end{aligned}
\tag{1}
$$

where c is the center and w is the width of the discretization box in DEC and q gives the relative normalizations of the two populations. We apply equation (1) to the $N = 5495$ stars

lying in the strip $7\rlap{.}''1\cos\delta + 0\rlap{.}''5 > \Delta\alpha > -7\rlap{.}''9\cos\delta - 0\rlap{.}''5$, and fit only in the region shown in Figure 1, i.e., $|\Delta\delta| < 12''$. (The reason for offsetting the center of this box from 0 will be made clear in Table 1, below.) We find that when w is left as a free parameter, the best fit value is consistent with $w = 6''$, the value expected due to discretization. We then fix w and rederive the other parameters. Next, we write a similar equation for the residuals in RA,

$$
\begin{aligned}
P(\Delta\alpha) \;=\; & \frac{\sec\delta}{2w}\Big\{q\Big[\mathrm{erf}\Big(\frac{c + w/2 - \Delta\alpha}{\sigma_1\sec\delta}\Big) - \mathrm{erf}\Big(\frac{c - w/2 - \Delta\alpha}{\sigma_1\sec\delta}\Big)\Big] \\
& + (1-q)\Big[\mathrm{erf}\Big(\frac{c + w/2 - \Delta\alpha}{\sigma_2\sec\delta}\Big) - \mathrm{erf}\Big(\frac{c - w/2 - \Delta\alpha}{\sigma_2\sec\delta}\Big)\Big]\Big\}.
\end{aligned}
\tag{2}
$$

We apply equation (2) to the $N = 5022$ stars in the strip $3\rlap{.}''3 > \Delta\delta > -3\rlap{.}''7$, and fit only in the region $|\Delta\alpha| < 12''\sec\delta$. The width is again consistent with the expected value, $w = 15''$, so we again hold w fixed. Table 1 shows our results. Here N is the total number of stars in the subsample and $N_1 = Nq$ is the number in the good-precision (σ_1) population. For both the α and δ directions, we find that $\sigma_1 \sim 1\rlap{.}''1$, $\sigma_2 \sim 6''$, and $N_1 \sim 4000$. That is, for more than half the full sample ($4000/6660 = 60\%$), Luyten actually obtained the stellar positions to a precision of $1''$ even though he recorded his results much more coarsely. For most of the rest, his measurement errors were similar to the discretization noise.

The offsets c may result from small systematic errors in Luyten's global astrometry, or from real offsets between his global frame and the ICRS that underlies Tycho-2 astrometry. In any case, these offsets are taken into account when we fix the intervals from which we draw stars to fit to equations (1) and (2).

However, Figure 2 shows that there is an additional population, an "outer halo" beyond what would be predicted by extrapolating the behavior of the inner two populations. The structure of the distribution shown in Figures 1 and 2 will lead us in § 3 to a "layered" approach to identifying NLTT stars.

Because some stars have much lower position errors than others, we suspect that they may also have much lower proper-motion errors. To test this, we divide the above sample into two subsamples, those lying with a slightly broadened ($16'' \times 8''$) rectangle and those lying outside it. For the stars in the rectangle, the RMS difference between the magnitudes of the proper motion as measured by NLTT and Tycho-2 is $18\,\mathrm{mas\,yr^{-1}}$, while for those outside the rectangle it is $24\,\mathrm{mas\,yr^{-1}}$. (Tycho-2 error are negligible in comparison.) Hence, the rectangle stars indeed have better proper motions. For the individual components of the proper motion vector, the corresponding RMS differences are $22\,\mathrm{mas\,yr^{-1}}$ and $27\,\mathrm{mas\,yr^{-1}}$ respectively. For random uncorrelated errors in RA and DEC, one would expect the magnitude RMS to equal the component RMS. The fact that the latter is larger is probably due to transcription errors in NLTT of the proper-motion direction (proper motion in NLTT is given as a magnitude

and a position angle of direction).

While the dispersions of this cleaned sample probably realistically characterize the intrinsic errors in the NLTT proper motions, they are lower limits on the RMS differences between NLTT and Tycho-2 for the catalog as a whole. This is mainly because binaries (which have been preferentially excluded from the sample by demanding one-one matches) can cause proper-motions to differ when measured over different timescales. We use these estimates to guide our approach to matching, but will evaluate the dispersions on the matched sample again in § 5 after carrying out the match.

3. Strategy to Match Bright NLTT Stars

We match NLTT sequentially to three proper motion catalogs of bright stars: Hipparcos, Tycho-2, and Starnet, each in succession containing more stars, but also generally poorer astrometry. That is, we first match to Hipparcos. We then remove from consideration all matched NLTT stars and match the remainder to Tycho-2 (or rather to the subset of Tycho-2 that is not associated with Hipparcos stars). We then repeat the procedure for Starnet.

Since NLTT has about 59,000 entries, of which almost 13,000 have counterparts in these three catalogs, we are especially interested in developing procedures that can match automatically as many of these as possible, thereby reducing to a minimum the number that require human intervention. For each catalog, we therefore begin by matching stars inside a ($16'' \times 8''$) rectangle. The chance that two unrelated high proper-motion stars will fall so close together is miniscule. We therefore place only very weak demands on matches: the magnitude of the vector proper-motion difference should be less than $100 \, \mathrm{mas \, yr^{-1}}$, and the "$V$" magnitudes should agree within 1.5 mag. For Hipparcos, we use the Johnson V mag given in the catalog. For Tycho-2, we use the catalog's V_T. For NLTT we use the "red" magnitude R_{NLTT} (which is actually quite close on average to Johnson V, Flynn et al. 2001) except when it is not given, in which case we adopt ($B_{\mathrm{NLTT}} - 1$) for the "V" mag. For Starnet, we use the red photographic magnitude which ultimately derives from the GSC 1.0. Of course, all these various magnitudes are not on exactly the same system, but because of the inaccuracy of photographic magnitudes, in particular those in NLTT, the systematic differences are not very important: we are interested only in a crude discrimination between stars of very different brightnesses. We conduct our search only for NLTT stars with $R_{\mathrm{NLTT}} \leq$ 14.0.

Singular matches from this rectangle search are accepted without further review. There are, however, many multiple matches in both directions. For example, if one component,

say A, of a CPM binary matches to a star in a given catalog, the other component, B, will almost always match as well. If the CPM binary is sufficiently wide to have a separate entry in the catalog being searched (Hipparcos/Tycho-2/Starnet), it may yield 4 "matches": A–A, A–B, B–A, B–B, of which the second and third are false. All such multiple matches are investigated, but in many cases they cannot be fully resolved because the true match to the companion is outside the rectangle or outside the catalog altogether. We return to this problem below. The matches are then removed from both catalogs, and a second search on the remaining NLTT stars is then conducted inside a radius $\Delta\theta < 120''$ but otherwise using the same criteria. These matches are also accepted without review: the main reason for separating the rectangle and circle searches at this stage is to reduce the number of multiple-matching candidates. After resolving double matches (where possible) we return to the rectangle, but loosen the criteria. We now demand only that the *magnitudes* of the proper motions be consistent within $80\,\mathrm{mas\,yr^{-1}}$ but place no constraint on the direction. This is to allow for transcription errors in the angle recorded in NLTT. We also loosen the tolerance on the agreement in "V" to 2.5 mag. The resulting new matches are then scanned manually. But again, since the chance that two unrelated high proper-motions stars will fall in the same rectangle is extremely small, virtually all of these matches are genuine. Next, we apply the same procedure to the $2'$ circle. All matches are again reviewed by hand, this time more critically. If, for example, the angle of the proper motion and the RA both disagree strongly, but the DEC agrees to within a few arcsec and the "V" mags also agree well, we assume that the match is real and that there are multiple transcription errors. Of course, we are more liberal for the regions where NLTT has worse-precision positions. Finally, we extend the search to $\Delta\theta < 200''$ and with the weak constraints on proper-motion and magnitude agreement. We review the results with extreme caution. (We do not apply this last step to Starnet because it contains spurious high-proper motion stars).

After these automated, and semi-automated searches are completed on one catalog, we move on to the next. After they are all complete, we move on to one final manual search. In it, we plot the unmatched NLTT, Hipparcos, and Tycho-2 stars, each using a different color, on a map of the sky using vectors whose length, orientation, and thickness represent respectively the magnitude and direction of the proper motion, and the "V" mag of the star. This allows us to find counterparts of NLTT stars with major measurement and/or transcription errors. For example, we find three counterparts that disagree in DEC by exactly $1°$ but otherwise are in perfect agreement. We even find one that disagrees by exactly $11°$ in DEC and about 9 minutes of time in RA. That this entry is a transcription error is obvious from the name that Luyten assigned to the star "$-65 : 2751$", which corresponds to its true declination, $\delta = -65°$.

We then return to the problem of binaries. We examine every pair of matches separated

by less than $2'$ in NLTT. In a large fraction of cases, these are each single matches of well separated stars, but we still check that we do not have the matches reversed, using the relative separation and orientation reported in the NLTT notes on CPM binaries. However, there remain many multiple NLTT matches to single stars in other catalogs, especially Hipparcos. We resolve these whenever possible using the *Tycho-2 Double Star Catalog* (TDSC, Fabricius et al. 2002) which contains PPM and photometry for multiple-component objects in Tycho and Hipparcos, both actually associated multiples and spurious optical doubles. This catalog also contains many binaries that are treated by NLTT as single stars. For some of these, NLTT contains a note that the entry is actually a binary and gives its separation and (usually) the magnitudes of its components. For others, NLTT regards the object as a single star. We make a note of all these cases for our future work on binaries, but for the present treat all single-entry NLTT stars as single stars. Some TDSC entries do not list a proper motion. For a large fraction of the cases we checked, the positions for these entries are also significantly in error. We therefore do not make use of these entries unless there is corroborating information (from NLTT or 2MASS) that the positions are correct. For cases where TDSC does not resolve an NLTT binary or where the TDSC entry does not contain a proper motion, we check to see if the star lies in the 47% of the sky covered by the 2MASS release. If it does, usually 2MASS resolves the binary and we substitute 2MASS coordinates for those of the other (e.g., Hipparcos) catalog. We also note whether we believe that the catalog's photometry can really be applied to each component (or whether this magnitude actually refers to a blend or to the other component). In the latter case, we adopt "*V*" from NLTT rather than the catalog. For binaries not covered by TDSC or 2MASS, or for which these catalogs do not resolve the binary, we record the two NLTT stars as an unresolved binary.

Finally, in the spirit of pushing our "bright" catalog as faint as possible for later comparison with the "faint" catalog of Paper II, we make a list of all NLTT CPM binaries for which one component is matched and whose fainter component has $R_{\mathrm{NLTT}} \leq 14.0$, but is not matched. We search for these directly in 2MASS, using the coordinates of the first component and the separation vector given in the NLTT notes to predict the position of the second. We incorporate these by assuming that the proper motion of the first component is also valid for the second.

4. NLTT Completeness

We study the completeness of NLTT at the bright end by comparing it to Hipparcos and Tycho-2. (Starnet cannot be used for this purpose because it contains spurious high proper-

motion stars). That is, we count the fraction of Hipparcos/Tycho-2 stars that were detected by NLTT as a function of various parameters. Before doing this, however, we first ask the opposite question: what fraction of NLTT stars were detected by Hipparcos/Tycho-2 as a function of R_{NLTT} (i.e., NLTT's proxy for "V")? The answer to this question, which is given by Figure 3, delineates the NLTT magnitude range to which our subsequent completeness tests apply.

4.1. Hipparcos/Tycho-2 Completeness Versus Magnitude

The bold curve in Figure 3 shows the Hipparcos/Tycho-2 completeness as a function of R_{NLTT}, i.e. it is the ratio of Hipparcos/Tycho-2 detections (shown by the upper of the two thin-line histograms) to NLTT detections (bold histogram). This completeness falls to 50% at $R_{\mathrm{NLTT}} = 11.6$, as a result of the Tycho-2 magnitude limit. Hence, our subsequent completeness tests apply approximately to NLTT stars with $V \lesssim 11.5$.

Figure 3 has several other features of note. First, there is a peak in NLTT detections at $R_{\mathrm{NLTT}} \sim 8.7$, which is then reproduced by the histogram of Hipparcos/Tycho-2 matches, as well as that of the Hipparcos-only matches just below it. This turns out to be an artifact of systematic "bunching" of NLTT magnitudes: a histogram of Hipparcos/NLTT matches as a function of Hipparcos V (not shown in the figure to avoid clutter) exhibits no such "premature" peak, but rather has a single, relatively broad peak at $V \sim 9.5$.

Note that Hipparcos/Tycho-2 completeness is $\sim 100\%$ only to about $R_{\mathrm{NLTT}} \sim 8.5$, falls to $\sim 95\%$ at $R_{\mathrm{NLTT}} \sim 9.5$, and then plummets rather sharply. Given that Hipparcos/Tycho-2 is itself quite incomplete significantly below $R_{\mathrm{NLTT}} = 11.6$, one might ask whether it can be used to reliably probe NLTT completeness all the way to this threshold. It can be so used if the reasons for NLTT non-detections are independent of the reasons for Tycho-2 non-detections. It is clear from the form of the completeness curve in Figure 3 that Hipparcos/Tycho-2 loses sensitivity with faintness. We will argue below that the NLTT non-detections are due to crowding, and not due to faintness, since NLTT goes much fainter than the limits of the modern catalogs. However, since crowding can exacerbate problems with detection of fainter objects, there could be some interplay between these two effects. We will comment on the role of this interplay in § 4.4.

4.2. NLTT Completeness Versus Proper Motion

Figure 4 shows the fraction of Hipparcos/Tycho-2 recovered by NLTT as a function of proper motion μ (as measured by Hipparcos or Tycho-2). The solid vertical line is at $\mu_{\rm lim} = 180\,{\rm mas\,yr^{-1}}$, the proper motion limit of NLTT. One expects completeness to fall by 50% at this point because half the stars that actually have this proper motion will scatter to lower values due to measurement error, and so will be excluded from the NLTT catalog. One therefore expects completeness to achieve its asymptotic value a few σ above this threshold. The two dashed vertical lines are at $\mu_{\rm lim} \pm 40\,{\rm mas\,yr^{-1}}$, which corresponds to $\pm 2\,\sigma$ for the better-precision NLTT stars, and about $\pm 1.5\,\sigma$ for the others. The completeness curve does indeed reach an asymptotic value of $\sim 90\%$ just beyond this point. Hence, at $\mu = \mu_{\rm lim}$ we expect the completeness to be $0.5 \times 90\% = 45\%$. The actual value is 42%. To avoid this threshold effect, we will restrict future completeness tests to stars with "true" (i.e., Hipparcos/Tycho-2) proper motions $\mu > 250\,{\rm mas\,yr^{-1}}$.

4.3. NLTT Completeness Versus Galactic Latitude

Figure 5 (bold curve) shows the fraction of Hipparcos/Tycho-2 proper-motion ($\mu > 250\,{\rm mas\,yr^{-1}}$) stars recovered by NLTT as a function of $\sin b$, where b is Galactic latitude. NLTT is virtually 100% complete away from the Galactic plane, but its completeness falls to about 75% close to the plane. This incompleteness is not symmetric: it is somewhat worse in the south. We will discuss the reasons for this in § 4.4. The histogram shows the underlying distribution of proper-motion stars, from Hipparcos/Tycho-2, as a function of $\sin b$. If these stars were distributed uniformly over the sky, then this histogram would be a horizontal line. One expects halo stars to be over-represented near the poles because the reflex of the Sun's motion is most pronounced in those directions. One also expects disk stars to be over-represented near the plane because their density does not fall off with distance in these directions. Plausibly, one can see both effects in the Hipparcos/Tycho-2 histogram. We will return to this conjecture in Paper II.

4.4. NLTT Completeness Versus Galactic Longitude

Figure 6 (bold curve) shows the fraction of Hipparcos/Tycho-2 proper-motion stars lying in the Galactic plane ($|b| < 15°$) that are recovered by NLTT as a function of Galactic longitude. While the curve is somewhat noisy, there is a clear increase in incompleteness over the interval $-80° \lesssim \ell \lesssim 20°$. This is the brightest contiguous region of the Milky Way,

which lends credence to the idea that NLTT incompleteness is traceable to crowding-induced confusion. The areas just south of the Galactic equator are on average brighter than the corresponding areas just to the north, so the asymmetric behavior seen in Figure 5 also lends credence to this hypothesis.

In § 4.1, we entertained the possibility that detection failures in NLTT and Hipparcos/Tycho-2 might be correlated which, if it were the case, would undermine the completeness estimates obtained from the fraction of Hipparcos/Tycho-2 stars recovered in NLTT. Figure 6 shows that this effect cannot be very strong, if it exists at all.

The expected number of high proper-motion stars as a function of Galactic longitude need not be uniform, and will in general depend on the model of the Galaxy. However, in any plausible model, the number should be the same looking in directions separated by 180° because NLTT stars are not at sufficiently large distances to probe the Galactic density gradients. Consequently, the distribution is a result of bulk kinematic effects, which should be identical in antipodal directions. Hence, if there were a correlation, one would expect that pairs of antipodal points with a positive difference in NLTT completeness would also have a positive difference in Hipparcos/Tycho-2 counts. No such pattern is seen in Figure 6. To make this point clearer, we plot these quantities against each other in Figure 7. If anything, there appears to be a weak anti-correlation.

In any event, the primary implication of Figure 5, namely that NLTT is essentially 100% complete away from the Galactic plane remains true, independent of these more subtle considerations. In Paper II, we will develop a more sophisticated version of the Flynn et al. (2001) bootstrapping technique to extend this completeness analysis to fainter magnitudes.

5. NLTT Proper Motion Errors

Altogether, we have matched 12,736 stars from NLTT to Hipparcos, Tycho-2, and Starnet (or in a few cases, to CPM companions of these stars that we found in 2MASS). We began this study by estimating the errors in positions and proper motions of the original NLTT catalog, but restricted to a relatively clean subset. Here we give the RMS differences between NLTT proper motions and those found in the three more modern catalogs. These differences can result from NLTT measurement errors or transcription errors, from real differences in the proper motion due to binarity, from misidentification of counterparts, or from proper-motion errors in the three modern catalogs.

The last of these four causes can be quite significant for the relative handful of stars near the magnitude limits of these catalogs, particularly Hipparcos. Indeed, we find that

when Hipparcos reports errors larger than $10 \, \mathrm{mas \, yr^{-1}}$, its true errors can be much larger than the tabulated errors. We also find that for the sample of stars common to NLTT, Hipparcos, and Tycho-2, the RMS tabulated Tycho-2 errors are substantially smaller than those of Hipparcos. Moreover, since these are established by a longer baseline of observation, they are more directly comparable to the NLTT proper motions in cases where the Hipparcos proper motion may be corrupted by a short-period ($P \lesssim 5 \, \mathrm{yr}$) binary. We therefore, first substitute Tycho-2 for Hipparcos proper motions whenever the former are available. For purposes of comparing with NLTT we then eliminate all stars with tabulated proper-motion errors greater than $10 \, \mathrm{mas \, yr^{-1}}$ in either direction. This removes 52 (0.6%) of Hipparcos stars, no Tycho-2 stars, and 23 (1.7%) of Starnet stars. After removal of these 75 stars, we expect that the proper-motion differences between NLTT and the three modern catalogs are dominated by the first three causes listed above.

Table 2 lists these RMS values for various subsets of the catalog. Here "Hipparcos" refers to NLTT stars found in Hipparcos, "Tycho-2" to stars found in Tycho-2 but not Hipparcos, and "Starnet" to stars found in Starnet, but not in either of the other two catalogs. "Better precision" stars are those with positions specified in NLTT to 1 second of time and $6''$ of arc (and generally lying in the range $-45° < \delta < 80°$), and "worse precision" stars are the remainder. When two NLTT stars, usually close components of a CPM binary, are matched to a single entry in the PPM catalogs, we compare the proper-motion measurements only once.

Table 2 shows that among the stars with nominally better positions, those inside the rectangle have consistently lower proper motion errors than those outside the rectangle. For Hipparcos and Tycho-2, the stars with nominally worse positions are intermediate in their proper motion errors between these two categories, indicating that they are also probably a mixture of intrinsically better and worse precision measurements. However, for Starnet, the proper motion errors of the stars outside the rectangle as well as those with nominally worse position errors both have significantly worse proper motion errors. This may indicate that these stars suffer many more false matches. We conduct a preliminary test of this hypothesis in the next section, although a full investigation will have to wait for Paper II.

6. False Matching Rate

There is an important potential channel for false matches in the work reported here: If none of the 3 PPM catalogs contain a counterpart to a given NLTT star, then our search procedure, which looks farther and farther afield, and with ever weakening demands on agreement in magnitude and proper motion, may ultimately find a marginally consistent

candidate match, which is nonetheless false. In fact, since we search the catalogs sequentially, we could even find a false match to, e.g., a Tycho-2 star, when the true counterpart of the NLTT star was in Starnet. Ultimately, in our full catalog, we expect to be able to correct the great majority of such false matches by checking the results of our bright-end search against those of the faint-end search that will be performed in Paper II.

For purposes of the present paper, in which we are presenting only statistical results and not the catalog itself, it is sufficient to measure the false-matching rate rather than finding every single false match. We can then check whether the rate of false matches is high enough to corrupt the statistics.

To this end, we conduct a preliminary version of the faint-end search that will be fully described in Paper II. We find all USNO-A stars lying within a $16'' \times 8''$ rectangle of each NLTT star, and then propagate these forward to the epoch of 2MASS using the NLTT proper motion. We then find all 2MASS stars lying within $5''$ of these predicted positions. We apply this procedure to the approximately 1/3 of the sky covered by the overlap of POSS I and 2MASS. (As already mentioned, high proper-motion stars are systematically removed from USNO-A in the regions south of POSS I.) We find from this exercise that about 3/4 of all NLTT stars in this region lie within the rectangle. That is, we obtain an independent check on $3/4 \times 1/3 = 1/4$ of all stars. Because of its very small size, the probability of a false match within the rectangle is extremely low.

We exclude from this search only the NLTT stars that were matched to Hipparcos in the first two search stages. Since these had rather strict criteria, and since the Hipparcos high proper-motion stars were largely drawn directly from NLTT, it is very unlikely that there are false matches among these. We manually inspect all discrepant matches. We find no false matches among the remaining Hipparcos stars, four false matches among the Tycho-2 stars, and eight false matches among the Starnet stars. In addition, we find that four of the Starnet matches, while probably correct, have proper motions that are seriously in error. We thus extrapolate that roughly 65 of the more than 12,000 bright NLTT stars that we have matched to Hipparcos, Tycho-2, and Starnet, are in fact incorrectly matched. Since this is well under 1%, it is unlikely to affect our overall statistical results in a major way. However, since roughly $4 \times (8+4)/(435+195) \sim 8\%$ of all Starnet matches lying outside the rectangle (or having inferior positions) are false matches or have seriously incorrect proper motions, false matching could be responsible for the exceptionally large proper-motion discrepancies reported for these stars in Table 2. Further investigation will be required in Paper II.

7. Comparison With Bakos et al.

We can gain some additional sense of the reliability and efficiency of our procedure by comparing our results to those of Bakos, Sahu, & Nemeth (2002), who manually identified the great majority of LHS stars and measured their PPMs from digitized plates (DSS1 and DSS2). As elsewhere in this paper, we restrict consideration to stars with $R_{\mathrm{NLTT}} \leq 14.0$, since the modern PPM catalogs to which we are matching NLTT contain essentially no stars beyond this limit.

There are a total of 2682 LHS stars contained in NLTT that meet this criterion, of which we match 1253. The vast majority of the rest have $R_{\mathrm{NLTT}} \geq 11.0$, at which magnitudes Hipparcos/Tycho-2/Starnet are rapidly becoming incomplete (see Fig. 3), and so many nonmatches are expected. There are a total of 6 bright nonmatches with $R_{\mathrm{NLTT}} < 10.0$ and an additional 14 with $10.0 \leq R_{\mathrm{NLTT}} < 11.0$. All 20 were detected by Bakos, Sahu, & Nemeth (2002) directly on the plates. We therefore use the Bakos, Sahu, & Nemeth (2002) coordinates to search for these stars in the PPM catalogs. Of the 6 in the brighter magnitude interval, 5 are in TDSC, but since either the primary or the secondary does not have proper-motion information and therefore their physical binarity could not be established, they were excluded from our identification procedure. The sixth (LHS 537) is not in any PPM catalog. Of the 14 in the fainter interval, one is in TDSC but was excluded for lack of proper-motion information, and the remaining 13 are not in any catalog. We conclude that our procedure is missing very few stars that are accessible through our catalogs, at least among the faster (LHS) stars.

Besides efficiency, we also use Bakos, Sahu, & Nemeth (2002) to test the reliability of our matches. Of our 1253 matches, Bakos, Sahu, & Nemeth (2002) failed to find 32. Of these 32, we judge 31 of our matches to be highly reliable based on the close agreement between the NLTT PPMs and the Hipparcos, Tycho-2 or Starnet PPMs that we recover. One match, a Starnet star, appears dubious. Half of the Bakos, Sahu, & Nemeth (2002) nonmatches are due to transcription errors in the LHS positions, typically of order 1°, which evidently prevented Bakos, Sahu, & Nemeth (2002) from finding the correct star. All but one of these LHS transcription errors were corrected in NLTT. (On the other hand, there were also new transcription errors present in NLTT but not LHS, including the star "−65 : 2751" [LHS 3674] mentioned in § 3, which has an 11° error in NLTT but is approximately correct in LHS.) All of the remaining 16 Bakos, Sahu, & Nemeth (2002) nonmatches for which we obtain good matches (13 from Hipparcos, 1 from Tycho-2, 2 from Starnet) lie within 135″ of their predicted NLTT positions. However, for these cases DSS2 data were either unavailable to Bakos, Sahu, & Nemeth (2002) or were of poor quality.

We search for discrepancies among the 1221 matches that are common to Bakos, Sahu,

& Nemeth (2002) and us. In the great majority of discrepant cases, there is good agreement between the Hipparcos/Tycho/Starnet PPMs and those of NLTT, leading us to believe that our identifications and measurements are correct. In most of these cases, Bakos, Sahu, & Nemeth (2002) have a note indicating that saturation or blending caused difficulties in their measurement. Less frequently, LHS position errors led Bakos, Sahu, & Nemeth (2002) to measure the wrong star (recognizable from its negligible proper motion). A bug in the Bakos, Sahu, & Nemeth (2002) computer program caused them to output a positive DEC when the star lay within 1° south of the equator, which accounted for about a half dozen of the discrepancies. In one case we traced the discrepancy to our error: we reversed the identifications of an equal-brightness binary relative to the convention of NLTT.

These tests confirm that our false matching rate is well under 1% and that we are missing much less than 1% of the stars that can be identified with the catalogs we are using.

REFERENCES

Alcock, C. et al. 2001, ApJ, 562, 337.

Bakos, G. A., Sahu, K. C., & Nemeth, P. 2002, Accepted for Publication in ApJS, astro-ph/0202164.

EROS Collaboration et al. 1999, A&A, 351, L5.

European Space Agency (ESA). 1997, The Hipparcos and Tycho Catalogues (SP-1200; Noordwijk: ESA)

Fabricius, C., Høg, E., Makarov, V. V., Mason, B. D., Wycoff, G. L., & Urban, S. E. 2002, A&A, 384, 180.

Flynn, C., Sommer-Larsen, J., Fuchs, B., Graff, D. S., & Salim, S. 2001, MNRAS, 322, 553.

Gizis, J. E. & Reid, I. N. 1997, PASP, 109, 849.

Hambly, N. C. et al. 2001, MNRAS, 326, 1279.

Hambly, N. C., Davenhall, A. C., Irwin, M. J., & MacGillivray, H. T. 2001, MNRAS, 326, 1315.

Henry, T. J., Ianna, P. A., Kirkpatrick, J. D., & Jahreiss, H. 1997, AJ, 114, 388.

Høg, E. et al. 2000, A&A, 355, L27.

Jahreiss, H., Scholz, R., Meusinger, H., & Lehmann, I. 2001, A&A, 370, 967.

Jones, E. M. 1972, ApJ, 177, 245.

Lasker, B. M., Sturch, C. R., McLean, B. J., Russell, J. L., Jenkner, H., & Shara, M. M. 1990, AJ, 99, 2019.

Lasker, B. M., Greene, G. R., Lattanzi, M. J., McLean, B. J., & Volpicelli, A. 1998, Astrophysics and Algorithms, E3

Lepine, S., Shara, M. M., & Rich, R. M. 2002, to appear in AJ., astro-ph/0203162.

Liebert, J., Dahn, C. C., Gresham, M., & Strittmatter, P. A. 1979, ApJ, 233, 226.

Liebert, J., Dahn, C. C., & Monet, D. G. 1988, ApJ, 332, 891

Luyten, W. J. 1979, 1980, New Luyten Catalogue of Stars with Proper Motions Larger than Two Tenths of an Arcsecond (Minneapolis: University of Minnesota Press)

Luyten, W. J. & Hughes, H. S. 1980, Proper Motion Survey wit h the Forty-Eight Inch Schmidt Telescope. LV. First Supplement to the NLTT Catalogue (Minneapolis: University of Minnesota)

Luyten, W. J. 1970, 1977, Luyten's White Dwarf Catalogues (Univ. of Minnesota, Minneapolis)

Luyten, W. J. 1979, LHS Catalogue: a catalogue of stars with proper motions exceeding $0\rlap{.}''5$ annually (Minneapolis: University of Minnesota Press)

Monet, D. G. 1996, American Astronomical Society Meeting, 188, 5404.

Monet, D. G. 1998, American Astronomical Society Meeting, 193, 112003

Monet, D. G. 2000, American Astronomical Society Meeting, 197, 111306.

Monet, D. G., Fisher, M. D., Liebert, J., Canzian, B., Harris, H. C., & Reid, I. N. 2000, AJ, 120, 1541.

Nesterov, V. V., Kislyuk, V. S., & Potter, H. I. 1990, IAU Symp. 141: Inertial Coordinate System on the Sky, 141, 482.

Oppenheimer, B. R., Hambly, N. C., Digby, A. P., Hodgkin, S. T., & Saumon, D. 2001, Science, 292, 698.

Reid, I. N. & Cruz, K. L. 2002, to be published in The Astronomical Journal, astro-ph/0202459.

Reid, I. N., Liebert, J., & Schmidt, G. D. 2001, ApJ, 550, L61.

Reid, I. N., Sahu, K. C., & Hawley, S. L. 2001, ApJ, 559, 942.

Röser, S. 1996, IAU Symp. 172: Dynamics, Ephemerides, and Astrometry of the Solar System, 172, 481.

Ryan, S. G. 1989, AJ, 98, 1693.

Ryan, S. G. 1992, AJ, 104, 1144.

Salim, S. & Gould, A. 2000, ApJ, 539, 241

Salim, S., Gould, A., & Olling, R. 2002, ApJ, 573, 000 (astro-ph/110628)

Schmidt, G. D., Liebert, J., Harris, H. C., Dahn, C. C., & Leggett, S. K. 1999, ApJ, 512, 916.

Scholz, R.-D., Meusinger, H., & Jahreiss, H. 2001, A&A, 374, L12.

Skrutskie, M. F. et al. 1997, in The Impact of Large-Scale Near-IR Sky Survey, ed. F. Garzon et al (Kluwer: Dordrecht), p. 187

York, D. G. et al. 2000, AJ, 120, 1579

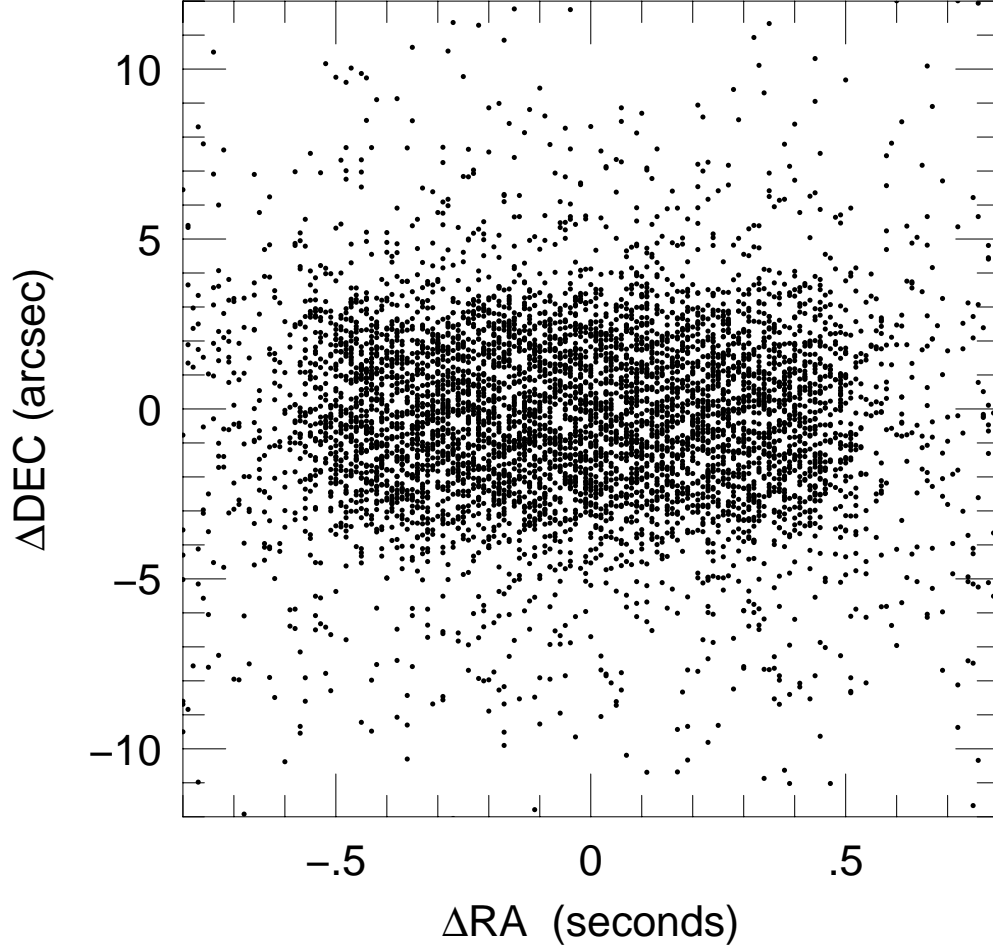Zacharias, N. et al. 2000, AJ, 120, 2131.

Fig. 1.— Differences between stellar positions as reported in NLTT and the very accurate positions of the same stars from Tycho-2, both evaluated in the NLTT epoch of 1950. The $(1\,\mathrm{s} \times 6'')$ rectangle that dominates this plot is caused by the fact that Luyten measured a majority of his stellar positions to a precision of $1''$, but reported them only to 1 second of time and $6''$ of arc.
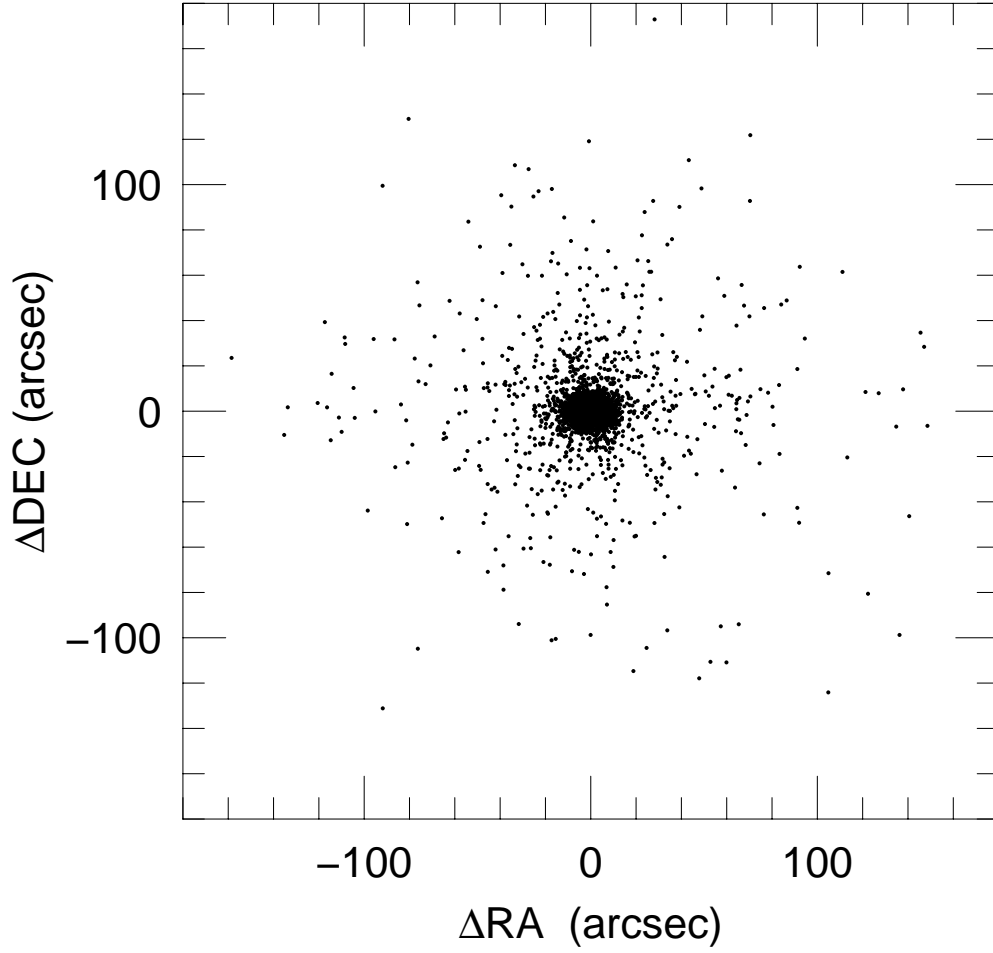
Fig. 2.— Same as Fig. 1 except that first, RA is now plotted in arcsec rather than in seconds of time, and second, the scale is much larger. Although most NLTT positions are quite accurate (see Fig. 1), there is a substantial "halo" of outliers, some that go well beyond the dimensions of this plot.
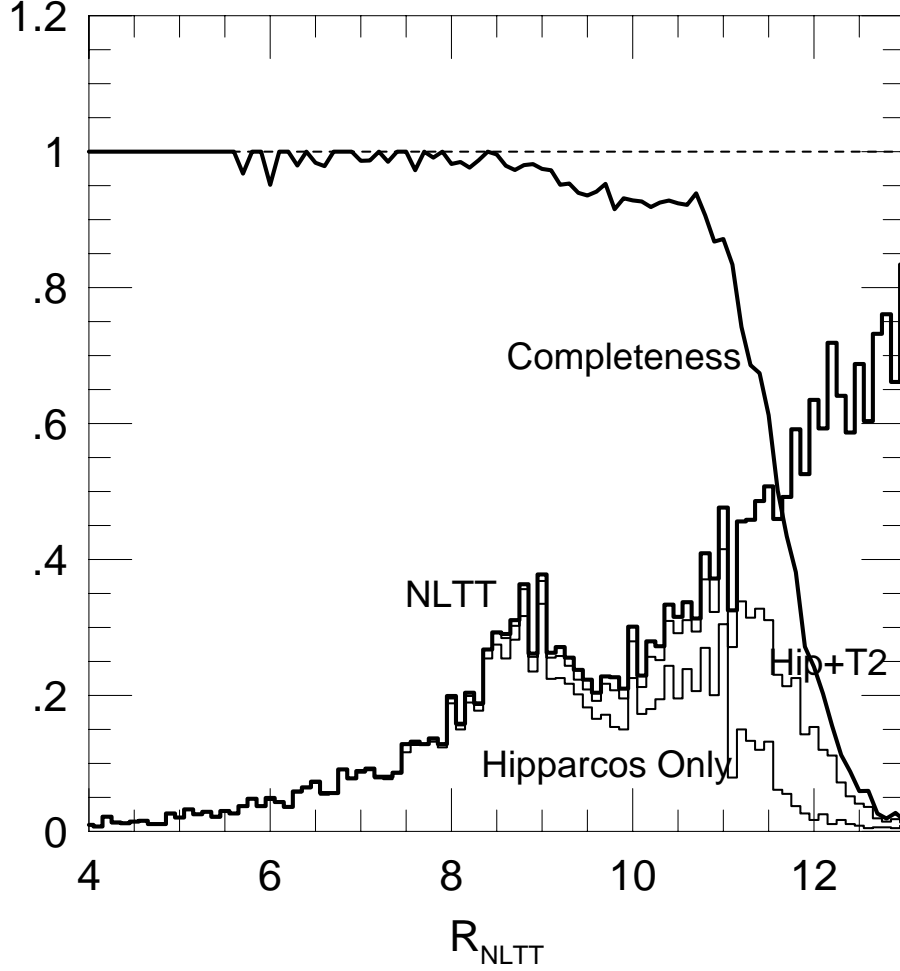
Fig. 3.— The completeness of the combined Hipparcos and Tycho-2 catalogs as a function of R_{NLTT} (roughly Johnson V) magnitude, measured from the fraction of NLTT stars (*bold histogram*) that are matched to one of these two catalogs (upper *thin-line histogram*). Also shown are the Hipparcos-only matches. The "bump" in NLTT detections at $R_{\mathrm{NLTT}} \sim 8.7$ is an artifact of NLTT mags. See text. Completeness falls to 50% at $R_{\mathrm{NLTT}} = 11.6$. Hence, the subsequent tests on completeness of NLTT apply directly to its brighter stars, $V \lesssim 11.5$. (All histograms are divided by 1000. The bin size is 0.1 mag.)
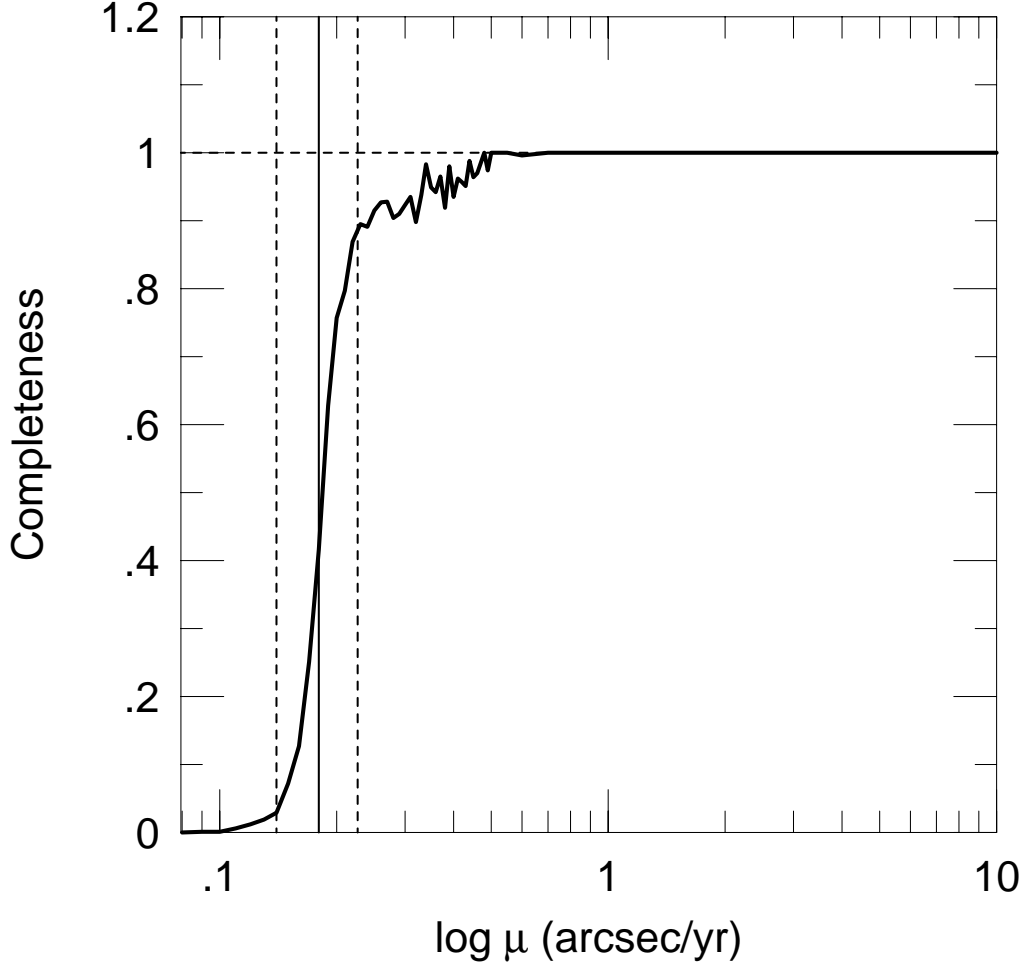
Fig. 4.— Completeness of NLTT (i.e., the fraction of Hipparcos/Tycho-2 stars recovered by NLTT) as a function of Hipparcos/Tycho-2 proper motion, μ. The solid vertical line shows the proper-motion limit of NLTT, $\mu_{\mathrm{lim}} = 180\,\mathrm{mas\,yr}^{-1}$, and the two dashed lines show $\mu_{\mathrm{lim}} \pm 40\,\mathrm{mas\,yr}^{-1}$, i.e., roughly the 1.5 to 2 σ errors in NLTT. The effect of this proper-motion threshold disappears by $\mu \sim 250\,\mathrm{mas\,yr}^{-1}$. Hence, subsequent completeness tests will be restricted to stars moving faster than this value.
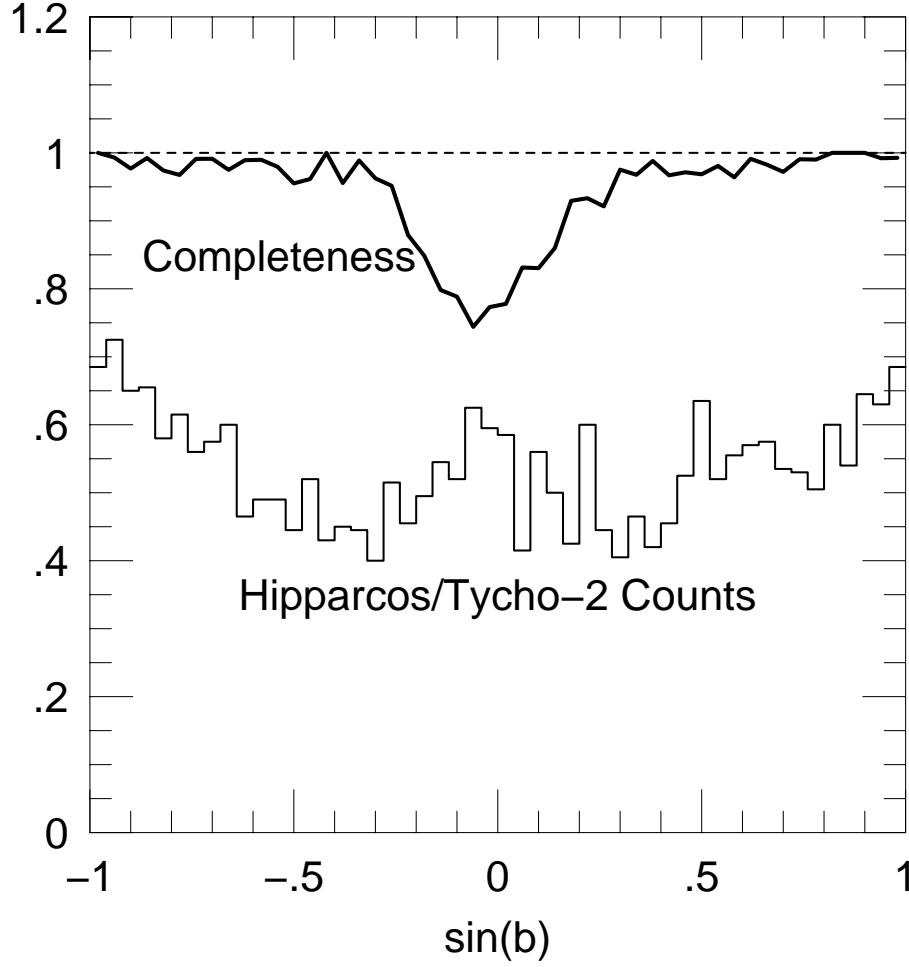
Fig. 5.— Completeness of NLTT (*bold curve*) as a function of $\sin b$ where b is Galactic latitude, i.e., the fraction of stars with $\mu > 250\,\mathrm{mas\,yr^{-1}}$ in Hipparcos and Tycho-2 (whose distribution is shown by the histogram) that are recovered in NLTT. (The histogram has been divided by 200. The bin size is 0.04) Incompleteness is significant only close to the plane, where it is somewhat skewed toward the south.
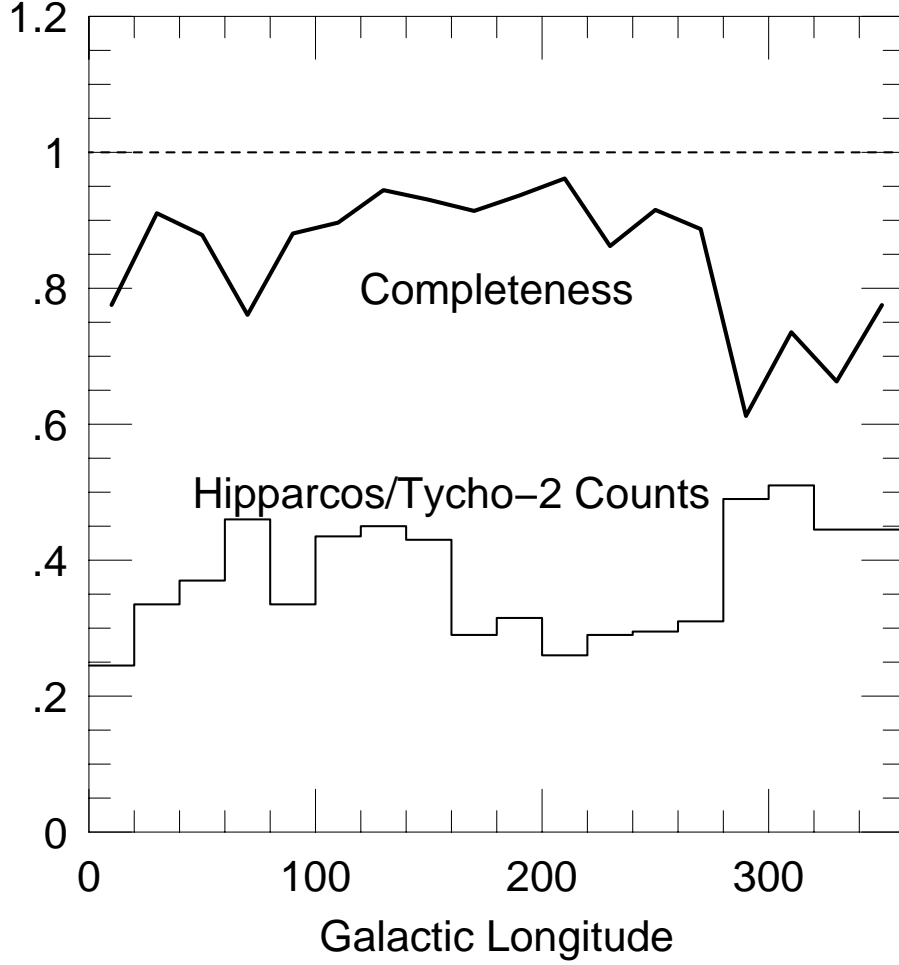
Fig. 6.— Completeness of NLTT (*bold curve*) as a function of Galactic longitude for the subset of stars lying close to the plane ($|b| < 15°$). Also shown is a histogram (counts divided by 200, 20° bins) of Hipparcos and Tycho-2 stars with $\mu > 250\,\mathrm{mas\,yr^{-1}}$ and $|b| < 15°$. The correlation (or lack thereof) between the two curves is analyzed in Fig. 7.
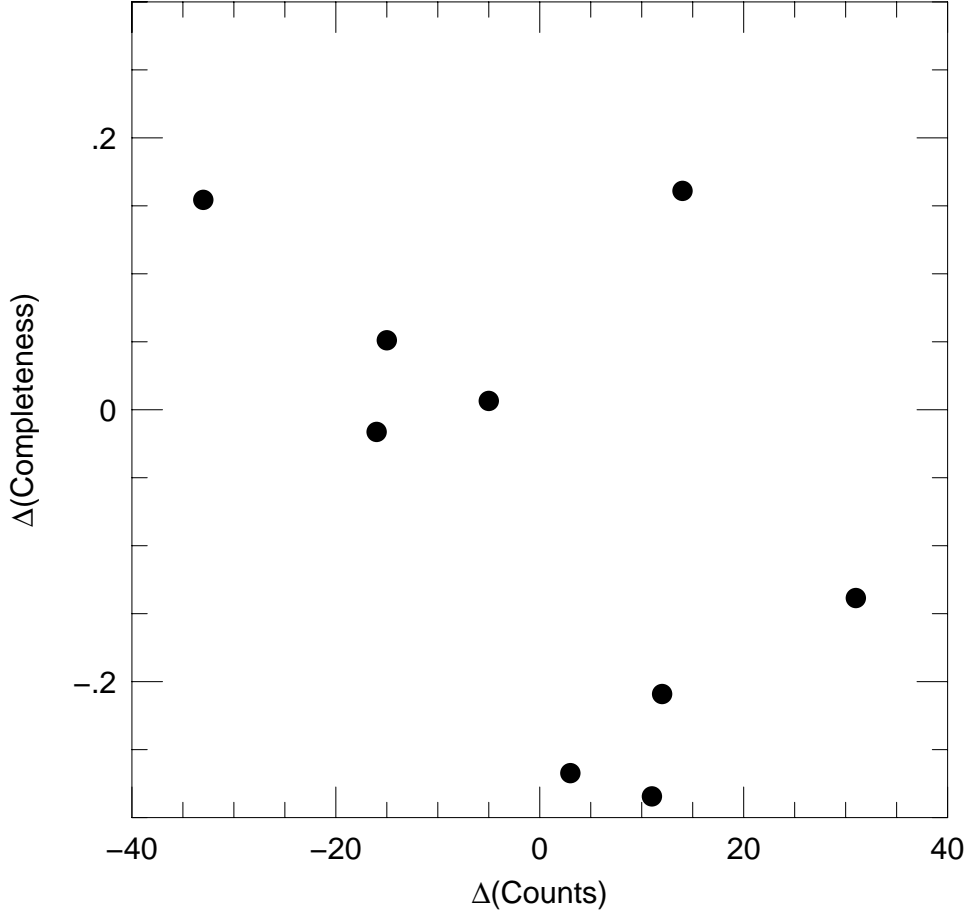
Fig. 7.— Differences in completeness at antipodal points $(\ell \leftrightarrow \ell + 180°)$ versus differences in counts of Hipparcos/Tycho-2 stars restricted to $\mu > 250 \, \mathrm{mas} \, \mathrm{yr}^{-1}$ and $|b| < 15°$ for the same longitude pairs. If Hipparcos/Tycho-2 completeness were correlated with NLTT completeness, one would expect these points to be positively correlated. If anything, they are weakly anti-correlated.

Table 1. NLTT Position Precisions

fit	σ_1	σ_2	c	q	N	N_1
RA	$1''\!.1$	$7''\!.0$	0.03s	0.774	5022	3887
DEC	$1''\!.1$	$5''\!.8$	$0''\!.15$	0.735	5495	4040

Table 2. NLTT Proper Motion Precisions

Catalog	Rectangle	Position quality	Number	$\sigma(|\mu|$ $\mathrm{mas\,yr}^{-1}$	$\sigma(\mu_\alpha)$ $\mathrm{mas\,yr}^{-1}$	$\sigma(\mu_\delta)$ $\mathrm{mas\,yr}^{-1}$
Hipparcos	In	Better	5261	20	22	25
	Out	Better	1623	31	33	32
	All	Worse	1284	24	28	34
Tycho-2	In	Better	1470	25	24	24
	Out	Better	1005	32	35	35
	All	Worse	438	28	32	42
Starnet	In	Better	738	25	27	24
	Out	Better	435	44	55	65
	All	Worse	195	42	57	45